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DEVELOPMENT OF A PLASMA RETROPULSE SHUTTER FOR SHIVA AND NOVA

L. P. Bradley, E. L. Orham, I. F. Stowers, and P. Koert

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LAWRENCE
LIVERMORE
LABORATORY
University of California/Livermore

LAWRENCE LIVERMORE LABORATORY

University of California Livermore, California 94550

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*Physics International, San Leandro, CA 94577

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ABSTRACT

A plasma shutter is being developed for a Nd:glass laser fusion system which, at an output spatial filter pinhole, produces a plasma of 10^{21} cm^{-3} to block target-reflected light from reentering the laser. A pulser using low-inductance capacitors and elastomer dielectric is switched with uv preilluminated railgaps to resistively heat a wire producing a plasma. The plasma generated within a nozzle and configured in a railgun geometry is projected across the optical beam path at $3.9 \text{ cm}/\mu\text{s}$. The optics are protected from the plasma. A scaled experiment is characterized, and a prototype shutter module is described.

OVERVIEW

We have developed a plasma source that can produce a plasma of 10^{21} cm^{-3} particle density and project it with a velocity of $3.9 \text{ cm}/\mu\text{s}$. This device will be used in the output spatial filter of the Nova Nd:glass laser system to propel a critical-density plasma across the optical beam path and block target retro-

reflected light. This paper describes the design of a plasma source appropriate to Shiva, presents a numerical model for the system, discusses the experimental characterization of the plasma, and describes the preliminary design of a higher-current prototype gun for Nova.

INTRODUCTION

An essential element in a laser fusion system is a device to minimize light retroreflected from the target.¹ The two schemes previously used with glass lasers are a Faraday rotator/polarizer² and an exploding mirror.³ The Faraday rotator/polarizer combination is reliable but adds to the nonlinear optical phase contributions, and its cost increases dramatically with aperture size. An alternative candidate is an inline plasma shutter.

The logical location for a fast plasma shutter is contiguous to the final spatial filter pinhole⁴ as shown in Fig. 1. Assuming a pinhole aperture of 1 mm and distance to the target of 15 m, the pinhole must close with an average velocity of $1 \text{ cm}/\mu\text{s}$. These dimensions are relevant to Shiva (the laser fusion test facility at LLL) and the test module we shall describe. Since the critical density for the absorption and reflection of $1.06\text{-}\mu\text{m}$ light is 10^{21} cm^{-3} , the shutter plasma must achieve this minimum density.

Of the several techniques for producing the required opaque plasma, most fall into a class based upon the rapidly induced sublimation of solid material.

This rapidly induced sublimation may be used directly as a plasma shutter, or it may drive a solid projectile⁵ (flyer or spall) across the optical beam path. The rapid sublimation may be produced by the resistive heating of a foil⁶ or by laser vaporization of a surface.⁷ We describe a particular shutter that uses the electrical sublimation of a thin metal foil or wire.⁸

A low-inductance parallel capacitor bank with uv-illuminated spark gaps produces a current rising at $5 \times 10^{12} \text{ A/s}$ and has a 1-ns jitter.⁹ The capacitors within the bank are optimally tuned to burst a wire, thereby producing a plasma, and to magnetically propel the plasma. The wire is contained within a nozzle and has the electrodes extending away from the capacitors in a rail-gun configuration. In our application, this geometry directs the plasma across the beam path and minimizes vapor leakage toward the optics. A dump tank collects the bulk of the plasma; baffles with a weak orthogonal magnetic field collect the plasma debris and protect the optics. The parameters are summarized in Figs. 2 and 3.

Current Nova chain design

Shiva chain design

Hypothetical Shiva upgrade (65% increase in output)

Legend

- ▶ Spatial filter
- N-cm aperture disk amplifier
- ∨ Polarizer-rotator-polarizer
- ↔ Turn mirrors
- Focus lens-windows-iris shields
- ✱ Spatial filters with plasma shutter

FIG. 1. Plasma shutter deployment in Nova and Shiva.

The pulser, plasma source, and collectors were housed in a Shiva 20-cm-aperture, $f/10$ spatial filter, and the plasma has been characterized. The plasma velocity was measured with Faraday cups and a streak camera. The plasma divergence was recorded with witness plates and Faraday cups. These data along with the known geometry permit a determination of the plasma density.

A self-consistent Lagrangian numerical program¹⁰ modeled the pre- and postburst behavior of the wire and included driving-circuit parameters and magnetohydrodynamic effects. It predicted the evolution of the plasma density and temperature. The code was essential to the design and optimization of the nonlinear circuit and useful for interpretation of the data.

- A plasma gun is located contiguous to a spatial filter pinhole
- The resistively heated foil is vaporized, heated, and magnetically propelled through a nozzle into the optical beam path
- A dump tank and baffle configuration protect the optics from vapor

FIG. 2. Plasma retropulse shutter.

A particular configuration, optimized for Shiva, contained a 3-mm-long, 125- μm -diam aluminum wire sublimed by a 100-kA peak current, as illustrated in Fig. 4. The measured plasma velocity was 3.9 cm/ μs , a value sufficiently fast to inject the plasma after the target-directed laser pulse had passed but before the reflected pulse returned. The plasma density, assuming single ionization for aluminum, exceeded 10^{21} cm^{-3} , a conservative value for blocking the 1.06- μm -wavelength light. Excellent agreement was found with these data and code predictions. A low-power probe laser was blocked as expected. The

Density = $1.5 \times 10^{21} / \text{cm}^3$
 Directed velocity = 4 cm/ μs
 Temperature = 30 eV
 Burst time = 50 ns
 Closure time = 100 ns
 Al wire, 6 mm $\times$ 125 μm ϕ
 Peak current = 120 kA
 Energy = 275 J

FIG. 3. Production of a directed plasma.

FIG. 4. Plasma retropulse shutter concept.

plasma volume was calculated (with LASNEX) to be large enough to prevent optical burnthrough by a 10-kJ, 5-ns laser pulse. Using a radiotracer technique, we determined that less than 10^{10} at./cm² (10^{-5} monolayers) were deposited on the optics per shot.

The prototype for Nova is designed with eight capacitors connected in pairs. The capacitor pairs are switched by four uv-preilluminated, midplane-triggered railgaps. A coaxial, low inductance, elastomer dielectric vacuum feedthrough connects the capacitors

FIG. 5. Plasma shutter experimental configuration.

to the wire. The wire is contained in a replaceable chip-nozzle subassembly, which will be automatically replaced after each shot. Design of the prototype is nearly complete, with selected elements undergoing checkout. The prototype should be available for testing in the fall of 1979.

The following describes the geometry of the present experiment and summarizes the primary physical processes involved. Following this, particular experimental data are presented along with a description of the larger Nova prototype design.

EXPERIMENTAL CONFIGURATION FOR SHIVA GUN PLASMA SOURCE

The experiment was contained in a multiport vacuum chamber that was constructed using a Shiva γ - δ spatial filter with $f/10$ optics, as shown in Fig. 5. An alternative set of $f/1.5$, 20-cm-aperture lenses located at the vacuum chamber ports was used for most of the experiments described here. The wire was located in the center of the chamber, near the focal point of the optics, as shown in more detail in Fig. 6. The nozzle assembly was contained in a removable circuit board as shown in Fig. 7.

The 3-mm-long, 127- μ m-diam aluminum wire was located between two electrodes in a 1-mm-deep,

150- μ m-wide slot in dielectric material. This slot formed a nozzle to confine the plasma during heating and to direct it across the optical beam path into a dump tank. Such a geometry increased the density at the focal region of the laser as compared to a freely expanding plasma, and also reduced the amount of vapor escaping toward the spatial filter optics.

The wire electrodes were connected via a low-inductance, parallel-plate transmission line to the pulser. The pulser contained six parallel Maxwell Type S, 0.22- μ F capacitors connected to the transmission line by six independent switches as shown in

FIG. 6. Plasma gun geometry.

FIG. 7. Experimental electrode and chip geometry.

Fig. 5, and in more detail in Fig. 8. The switches were midplane-triggered, uv-illuminated, pressurized-air spark gaps which we retrofitted into Tachisto 50I switch bodies. The trigger configuration is similar to that used in the Pulsar SW 50K gap but provides lower net inductance. The trigger was fed through the trigger pin and first arced across the illuminator, which was connected to ground via a current-limiting resistor. The small gap thus provided preillumination to the main gap and also served to sharpen the risetime of the trigger pulse. Such an arrangement provided jitter with a rounded trigger pin and was not as sensitive to erosion as the typical sharp-edged mid-

plane trigger gap. An equivalent circuit of this configuration is shown in Fig. 9.

In this configuration, the pulser could be charged to 50 kV and provided a current rising at 5×10^{12} A/s. These main spark gaps, when triggered with a fast trigger pulse, provided nanosecond jitter and hence excellent current sharing of the parallel gaps and synchronization with the laser and diagnostics. When connected to the foil, including all inductances, the current had a quarter period of 300 ns. The vacuum feedthrough for these particular tests tripled the source inductance.

DIAGNOSTICS

A set of electrical diagnostics was used to establish the pulser characteristics, and a set of plasma diagnostics was developed to characterize the primary features of the plasma.

Electrical circuit monitors recorded the charge voltage of the capacitors and the current and voltage near the foil. Witness plates of glass and/or metal

were used to collect the vapor and enabled us to record the angular distribution of the emitted plasma.

A Faraday cup was constructed from a metallic disk connected to a BNC connector with a negative bias of 155 V. It was coaxially contained in a grounded metal cylinder with two axial pinholes of 250 μ m diam located at 1 cm intervals between the Faraday

FIG. 8. One nanosecond jitter, low-inductance switch geometry.

FIG. 9. Equivalent circuit of plasma gun and trigger.

cup and the plasma source. Separate pumpout ports eliminated residual air from this assembly.

Plasma front velocity was recorded with a TRW streak camera focused along the laser beam optical axis and with the slit oriented parallel to the plasma expansion axis.

A cw YAG probe laser with a $100 \text{ \AA}$ narrow-band filter and uv blocking filter was used with an EG&G SGD-100A photodiode to monitor shutter closure. The photodiode was biased at 100 V for $1 \text{ } \mu\text{s}$ during the period of interest. The plasma diagnostics are summarized in Fig. 10 and the geometry is shown schematically in Fig. 11.

Velocity	Faraday cup, streak
Angular distribution	Witness plates
Density	Geometry plus above items
Small signal closure	CW laser
Large signal closure	Lasnex
Plasma leakage onto optics	Radiotracer, Faraday cup, witness plates

FIG. 10. Diagnostics.

FIG. 11. Plasma shutter diagnostic geometry.

MODEL

Because the wire constitutes a nonlinear load to the electrical source, and because the plasma properties are coupled to the pulser, we developed a program to model the system. The program was necessary to scale up from an initial experiment to the Nova configuration, to select an operating point, and as a guide in the interpretation of the data.

The program is a self-consistent Lagrangian numerical program to model the pre- and postburst features of an exploding foil. This formulation in-

cludes the driving-circuit parameters and magneto-hydrodynamic effects. It provides the evolution of the plasma density and temperature. The model is relatively simple, has fast execution time, is presently two dimensional and it provides the essential features of the plasma behavior.

Selected results are shown in Figs. 12-14, which show the power delivered to the plasma, the plasma temperature, and the mean plasma velocity, respectively.

FIG. 12. Power delivered to plasma heating and magnetic propulsion phases.

The resistive mode, incorporates pre- and post-burst stages after Logan and Lee⁶; initially a linear variation of foil resistance to burst is assumed.

$$\rho = \rho_0(1 + \alpha\Delta T) \quad (1)$$

where ρ is the ambient resistivity and α is the temperature coefficient. The time of burst is determined by the specific action⁶

$$a = \int_0^{t_B} J_e^2(t) dt = 6.75 \times 10^{16} \text{ A}^2\text{s/cm}^4 \quad (2)$$

where J_e is the current density in the wire and t_B is the time of burst. The specific action at burst

has been empirically determined to be invariant and characteristic of each wire material.^{6,11} The value of a , given above, is for aluminum.

The postburst resistivity was formulated to be a combination of electron-atom and electron-ion collisions. The degree to which each of these collisions determines the resistivity is weighed by the level of ionization of the vapor. Bond¹² suggests that the resistance for electron-atom collisions is a function of $T^{1/2}$. However, for our simple model a better fit with experimental data (from past exploding-wire experiments) was obtained when a linear temperature dependence was inserted. Spitzer's formulation¹³ for a fully ionized plasma was used for the electron-ion collisions. The postburst resistivity model used is

FIG. 13. Plasma temperature as a function of time.

$$\rho(T) = \rho_b \left[(1-\xi) \left(\frac{T}{T_b} \right) + \xi \left(\frac{T_b}{T} \right)^{3/2} \right], \quad (3)$$

where ρ_b is the burst resistivity, T_b is the burst electron temperature, and ξ is the degree of ionization. ξ is calculated as

$$\xi = \frac{1}{(1+f)^{1/2}}, \quad (4)$$

where f is obtained from the ionization equation which has the form

$$f = K \frac{\rho_m}{T_{eV}^{1/2}} \exp(I_n/T_{eV}), \quad (5)$$

where ρ_m is the material density in g/cm^3 , T_{eV} the electron temperature in eV, and I_n the ionization energy, with $K = 22.2$ for aluminum.

With the resistance variation described above, and considering magnetic forces, we can distinguish two phases that determine the plasma velocity, as shown in Fig. 14. In an initial resistive heating phase, near the time of burst, the energy is transferred to the plasma particles, thus increasing the random kinetic temperature of the plasma. Thereafter a magnetic propulsion phase ensues, during which the $\mathbf{J} \times \mathbf{B}$ force acts on the plasma to increase its directed velocity. In particular it is primarily the magnetic field of the rails (feeding the wire) crossed with the self-current of the wire that asymmetrically causes the propulsion.

FIG. 14. Measured and calculated plasma velocity.

An important feature of this process is that by tailoring the current pulse history, and for a specific wire material and size, we can to some degree separately control the plasma temperature and plasma

velocity. Such control enables us to limit the divergence of the plasma while maintaining a highly directed velocity. In Appendix A we show evidence of this control by application to an opening shutter.

EXPERIMENTAL RESULTS

The experimental results pertain to a 125- μ m-diam, 3-mm-long aluminum wire connected as described with the pulser charged to 20 kV. All data correspond to the final nozzle arrangement unless otherwise specified.

The plasma velocity was determined from streak camera photographs with the slit parallel to the plasma axis, and by a Faraday cup located 39 cm from the wire and axially centered on the plasma axis. A streak camera photograph and Faraday cup record are shown in Fig. 15. In Fig. 14 a densitometer scan of the streak photograph was made, and isodensity profiles generated for specific axial displacements. The Faraday cup trace is also shown, translated and linearly scaled in time to correspond to the streak data. These results are also superimposed in Fig. 14 for comparison with the model prediction. The agreement between the two independent velocity measurements and with the model is excellent. The model was developed separately from the experiment and not iterated with these experimental data.

The angular distribution of the plasma was recorded on glass witness plates located 8.9 cm from the wire and configured as shown in Fig. 11. Additionally, metal witness plates were used and compared to ensure that surface charging of the plates was not important.

An array of pins was placed in front of the plates to cast shadows from the vapor and thereby establish that the aluminum vapor traveled in straight lines from the nozzle throat to the wire. By placing partitions radially between the plates we established that backscatter from the plates and redeposition onto the plates was a second-order effect. There was, however, evidence of backscatter from the plates onto the electrode assembly and onto the optics. This effect did not appear to distort the angular measurements and will be discussed separately.

The chip was configured as shown in Fig. 11, and the electrodes were tapered 20° from the axis as shown in Figs. 6 and 7. Under these conditions the aluminum vapor was collected on glass witness plates. These plates were registered and scanned with a densitometer and the data digitized. A resulting isodensity plot and a radial density plot on the centerline of the distribution is displayed in Fig. 16. The peak optical density was 0.3. Using the tabulated optical density as a function of thickness for aluminum,¹⁴ we determined that to first order the aluminum from the wire was deposited on the plates. Since our primary concern was to determine the angular distribution of the vapor, we did not examine in detail the backscattering of the vapor from the plates.

(a)

(b)

FIG. 15. Streak photograph and Faraday cup trace for plasma shutter; (a) streak photograph, 1 μ s full sweep; (b) Faraday cup.

FIG. 16. Angular distribution of plasma for plasma shutter.

To obtain the final nozzle and electrode shape described, we varied the ratio of depth to width and established that this nozzle gave a reasonably narrow divergence while minimizing the nozzle depth. The shoulders on the nozzle were developed to minimize the debris scatter toward the optics. It is assumed that without the shoulders, observed particle scatter toward the optics was caused by particle scatter from the nozzle exit and/or ultraviolet ablation of the nozzle exit. For electrodes not tapered at 20° (i.e., parallel), there was an asymmetrical band of vapor directed on the laser plasma axis and continuing toward the optics. This was believed to be caused by particle scatter from

the electrode surface. The final geometry resulted from an empirical study of these several effects on the angular distribution, and was selected to maximize the vapor density on axis while minimizing scatter toward the optics.

The geometry under consideration has been selected and optimized to be retrofitted into an existing Shiva γ - δ spatial filter to block a 1-mm-diam pinhole. The shutter in use is located 2 cm downstream (toward the target) of the pinhole, where the optical beam has expanded in cross section. The beam passes 4.5 mm above the initial position of the wire. The geometry for reference is shown in Fig. 6.

FIG. 17. Measured optical shutter action at 1.06 μm .

The particle density distribution in the interaction region can be determined from the preceding data, the geometry, and the initial wire size. One dimension, along the axis, was bounded by the electrodes and thereby fixed as confirmed by the witness plates. The distribution along the laser axis was evaluated from the angular witness plates data. The distribution along the plasma axis was determined from the Faraday cup data. The peak density was $1.5 \times 10^{21} \text{ cm}^{-3}$, assuming single ionization. The critical density for 1.06- μm light is 10^{21} cm^{-3} . With the stripping and multiple ionization that would be caused by an intense laser beam, the density in the interaction region should be more than adequate to stop the retropulse.

We have examined small-signal shutter action with a cw 1.06- μm YAG probe laser in a similar geometry and demonstrated closure as shown in Fig. 17. The optical beam was blocked as expected. However, since a full-power (worst case) Nova beam has more power than Shiva, we had no way to fully test the Nova shutter, and therefore Max and Rosen¹⁵ simulated the Nova conditions using LASNEX. The results

of such a calculation are shown in Fig. 18 along with the assumed parameters. The initial plasma characteristics have been scaled with our code to those expected for the Nova shutter. In these simulations, the assumed full retropulse only burns through 2% of the plasma thickness. However, other simulations have shown that if the plasma is located too close to the focal region, burnthrough (hole boring) might be possible. Additionally, for a plasma which was 50% under critical density, no burnthrough was observed (in simulation). But in less-dense plasma, of otherwise the same characteristics, some leakage was observed before the plasma was stripped sufficiently to block the remaining beam.

The next important consideration was to quantify the vapor leakage toward the axis. However, it was necessary to ensure that leakage did not occur from chip disintegration or from leakage around the chip sides.

By testing several chip materials we established that shock caused cleaving along weak axes and in some cases caused rear surface spall. Rather than

FIG. 18. Predicted penetration into shutter plasma by Nova laser pulse.

extensively studying the failure modes of chips, we held the operating voltage to 20 kV, limited the wire size to 125- μm diam, and used polyimide chips. This ensured chip survival, thus preventing leakage and minimizing chip material in the plasma. We note that of those materials tested Ryton¹⁶ survived best, showing only slight distortion after the shot, whereas the polyimide shattered for higher voltages and/or larger diameter wires.

Cladding the chip surfaces contiguous to the electrodes with 250- μm -thick copper provided a gasket and prevented gas leakage from the chip sides. This copper also served as a replaceable electrode surface which when damaged at its juncture with the wire could be replaced on each shot. The chips were not reused for data shots.

A dump tank was located directly opposite the nozzle to collect the vapor. The sticking coefficient for 30 eV aluminum ions is unknown, but according to data from other experiments,¹⁷ we expect it to be $\lesssim 0.5$. We had noted backscatter from witness plates in qualitative agreement with a sticking coefficient < 1 . As an aside, in an early version of the dump tank (a specially contoured aluminum tank with a deflection plate located 10 cm from the wire) the deflection plate was severely ablated by the plasma and had significant backplash.

Since cooling might increase the sticking probability, particularly for slower secondaries, we constructed a liquid- N_2 -cooled copper dump tank 20 cm diam by 60 cm long, which was lined with copper wool. Conceptually we expected the plasma to travel to the far end of the dump tank before scattering, and then have a large rough surface available for scattering and capture. An insulating sleeve surrounded the gun electrodes as shown in Fig. 6 and interfaced with the dump tank. Additionally, apertures along the beam path collimated any vapor leaking toward the lenses. Permanent magnets provided a 0.1-T magnetic field orthogonal to the laser axis to deflect ions traveling toward the axis. Such a field can only be partially effective because the Debye length is shorter than the plasma characteristic dimension.

With the experiment thus configured we measured leakage by a radiotracer technique and subsequently verified the measurement with a Faraday cup. To conduct the radiotracer experiment we activated a 125- μm -diam copper wire in the LLL reactor via neutron bombardment. We monitored the annihilation photons from the B^+ decay of Cu^{63} , using a detector that had been set up for Shiva radiochemistry.¹⁸ A wire was vaporized in the plasma gun and leakage collected on witness plates located along the laser axis at 17.5 and 152 cm from the wire, the latter position being

the lens location from the Shiva γ - δ spatial filter. At the far location we obtained 2.4 counts/min. After a 1 week decay time we counted an unfired but simultaneously irradiated wire with the same detector. (The wait was required to reduce the counts per minute and thereby avoid the possible ambiguity of a detector recalibration.) The counting was repeated on a second detector. All detector threshold was 0.3 counts/min. Background of typically 0.8 counts/min was subtracted from these data for each sample. This measurement corresponded to 10^{10} at./cm² deposited on the optics at a distance of 152 cm from the wire. These data were reproduced on four separate runs within 10%.

Once we had improved the signal-to-noise ratio on the Faraday cup, we confirmed the magnitude of the leakage fluence of particles and established that their velocity distribution corresponded to thermal (30 eV) ions. Note that the aperture of the Faraday

cup for this measurement was smaller than the Debye length, thereby permitting separation of the ion component. The magnitude of the leakage fluence of the radiotracer (which measures all particles) agrees with the fluence of the Faraday cup (which measures only directed high-velocity ions). Thus we conclude that particles backscattered from the dump tank contribute only a second-order amount to the leakage vapor.

Since a monolayer is approximately 10^{15} at./cm² and we detected a leakage of 10^{10} at./cm² at 152 cm from the wire, we concluded that the optics will probably have to be resurfaced for other reasons before debris contamination perturbs the laser beam. In addition, the near and far witness plates showed that the leakage fluence falls by $1/r^2$. For application in Nova where the optics will be 10 times farther removed, we expect contamination to be reduced significantly and hence not be a problem.

NOVA PROTOTYPE MODULE

The output spatial filter in Nova is assumed to be $f/26$ with a 4-mm-diam pinhole, as based on the Nova baseline design. The Shiva output filter was $f/10$ with a 1-mm-diam pinhole. The shutter nozzle must be placed downstream (optically) from the pinhole such that the optical beam diameter is sufficiently large to prevent optical hole boring. At such a location the electrodes must be 8 mm apart, and the plasma must thus be 6 mm diam orthogonal to the optical axis. As the plasma diameter is determined by the electrode separation, so the plasma thickness is determined by the divergence from the nozzle.

The distance from the shutter to the target is 41 m, so the closure time must be less than 270 ns. In selecting the plasma velocity, we have noted in Faraday cup records that hydrogen and carbon come off initially at higher velocity than aluminum, as expected from an equilibrium plasma, and thus the closure velocity must be selected such that no hydrogen is in the optical path during laser output, but that the aluminum plasma is in position coincident with a retropulse.

Having established the required shutter characteristics, we next ran a parameter survey with the code to determine the pulser characteristics. We expect the code prediction to be reasonably accurate since it agrees with our present pulser design (which incidentally was already scaled from a previous configuration), and agrees over two orders of magnitude within 10% for flyer plate data (although in the flyer data the

magnetic propulsion phase is unimportant). Additionally, other estimates were also made which support the point design. We placed an important constraint on the design that all components be almost standard elements and be within the state of the art. By so constraining the design, we were able to select from among several competitive elements and concentrate on improving the reliability of those elements.

Some primary requirements of the pulser circuit are as follows. Since $J^2\rho$ heating occurs primarily at burst, we require a high current at burst, and hence a fast current risetime. This results in the low inductance circuit. Since $\mathbf{J} \times \mathbf{B}$ propulsion occurs after burst, the current must continue to flow at an increasing rate after burst; alternatively stated, burst must occur early in the current waveform. Other considerations have led us to consider tuned circuits that optimally pump the plasma. Because of the desire for simplicity, we have selected a single-frequency circuit for the baseline with the option of fine tuning later.

The final prototype design contains eight parallel 0.66- μ F, 20-nH, 50-kV capacitors connected in parallel through four 10-nH rail gaps via a coaxial 3-nH vacuum feedthrough to the load. The total pulser inductance is 10 nH. As presently envisioned, this design is shown isometrically in Fig. 19 and in cross section in Fig. 20.

The equivalent circuit of the pulser is shown in Fig. 9. A logic signal is incident on the trigger amplifier

FIG. 19. Nova plasma shutter geometry.

FIG. 20. Plasma shutter pulser cross section.

FIG. 21. Preilluminated rail gap.

which consists of a Pulsar Pulsepak 10A and transformer. A coaxial two-stage Marx, which is charged by the main power supply, is triggered by this unit and provides an output of 100 kV rising in 8 ns to trigger the railgaps. A switch as used in the Marx is shown in Fig. 8 and has uv preillumination.

A detailed view of the railgap, one of four parallel units, is shown in Fig. 21. The railgap has semi-Rogowski electrodes and a longer graded trigger blade. The trigger pulse is fed through a peaking gap on the end with its spark located on axis with the rails, thereby preilluminating them. The switching gas is 20% SF_6 and 80% Ar. The function of the uv pro-

duced¹⁹ primarily in the argon is to provide free electrons and metastable states in the main gap region. These electrons help in initiating avalanches and streamers, and also cause precise closing²⁰ of the streamers. The system shown has been extensively tested and characterized. It provides nanosecond jitter from logic signal to railgap closure. With the dc charge voltage, it also provides multichannel operation. This latter behavior is important to gap erosion but not to shutter operation. It is also important with this particular railgap that operation is somewhat insensitive to rail edge sharpness, thus tending to maintain reliability with age (i.e., less blade erosion).

The electrodes are currently fabricated from low-lead brass. During the next year we will continue to examine Schwarzkoph K25 tungsten, Poco AXF5QC and ACFIOQC graphites, and other materials to minimize erosion and most importantly, minimize prefire. Better electrodes are a major goal of our program.

The 0.66- μ F, 20-nH, 50-kV capacitor was developed by Maxwell for this application; it is similar to the Garching type.²¹ It has a plastic case with a parallel rail header, and the internal construction is similar to the proven Sylac capacitor. Internal inductance is 20 nH and the expected life is 10^6 shots at 80% reversal.

The dielectric is a special urethane elastomer that is cast in the shape required for the coaxial feed-through. The coaxial design minimizes the number of

exposed high voltage edges. The effect of surface corona is minimized by employing a semiconductor coating. The urethane is designed to minimize surface tracking under or between capacitors and/or switches. Its elasticity will restore its shape and in particular its contact with the conductors after a magnetically induced mechanical impulse.

The pulser is housed in an electromagnetic shield and backfilled with either atmospheric pressure SF₆ or a fluorocarbon gas. Two trigger generators are located in the shield and provide a trigger pulse to the blade via separate peaking gaps. Similar redundant triggering used for the Shiva ignitrons has proven quite reliable.

CONCLUSIONS

We have developed a plasma source to project a critical density plasma across an optical beam path sufficiently fast to block a retroreflected laser pulse. Using parameters relevant to Shiva, we have characterized and optimized the circuit and plasma characteristics. This work has yielded a significant advance in the state of the art for exploding foils and wires. The pulser, although advanced, is conservative by design, with emphasis on operating reliability.

The plasma diagnostics have purposely been simple with emphasis on obtaining certain relevant plasma parameters. The leakage toward the spatial filter optics as measured by a radiotracer technique was at the state-of-the-art limit and completely undetectable by the usual surface analysis probes (SIMS, etc.). How-

ever, it was a measurement to predict the optics lifetime for thousands of shots based on a single shot. We will consider holography as a diagnostic on the Nova prototype to determine the effect of possible instabilities that might produce striations in the plasmoid.

For the pulser we have developed and will continue to develop reliable components with particular emphasis on switching. The pulser has high current, low inductance, and nanosecond jitter. All sparkgaps use uv preillumination to pulse sharpen the trigger, minimize jitter, and minimize the effect of electrode erosion with age. The elastomer dielectric minimizes surface corona and tracking. The system is coaxial and enclosed to minimize inductance, edge effects, and electrical noise.

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APPENDIX A.

PLASMA OPENING SHUTTER EXPERIMENT

There is a need for a faster-opening ASE (amplified spontaneous emission) shutter. Having worked with the plasma closing shutter, we hypothesized that we could make a shutter open an order of magnitude faster than a rotating wheel (the baseline ASE shutter for Nova).

By placing a very thin foil across the beam path to block the ASE and then driving a very high current through it, we expected to remove it in ~ 100 ns. The current would vaporize the foil and in a railgun geometry propel it out of the beam path. The key feature, verified by our 2D model, is that a small foil will burst early in the current pulse and clamp its temperature. Thereafter a very high current will provide sufficient magnetic field to contain the plasma debris at least long enough until the plasma enters a dump tank, thereby protecting the optics. To reiterate, the foil would blow up in full view of the optics but never reach the optics.

To test this hypothesis, we used our existing Shiva

plasma shutter module with only the electrodes modified to hold the foil. We conducted a parametric test for various foil sizes to confirm the divergence and velocity behavior of the plasma. These data were recorded with a Faraday cup, witness plate, and streak camera. The collimation and containment of the plasma for thin foils were dramatically demonstrated. Next we probed the plasma with a Q-switched YAG laser pulse. The incident and transmitted optical pulses were monitored by photodiodes. This confirmed the opening nature of the shutter with no attenuation observed for the transmitted pulse.

We demonstrated an opening time of 600 ns for a 2- μ m-thick aluminum foil blocking a 1-mm-diam aperture. The absolute opening time is probably 100 ns.

We have unambiguously demonstrated that such a shutter works. The fraction of the wire fluorescence reaching the target must be assessed in more detail. Aside from this, the shutter appears to be a viable option for Nova.